Project Title: Literature synthesis and meta-analysis of tree and shrub biomass equations in North America

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I. Abstract

Over three thousand published equations purport to estimate biomass of individual trees and/or branch, bole, bark, or foliage components for North American tree species. These equations are often based on small samples and often provide different estimates for trees of the same species. Therefore, it is no simple task to select appropriate consistent biomass equations for carbon estimation. A previous study addressed this issue by devising 10 new equations that estimated biomass for all species in North America (Jenkins et al. 2003). In that study, we used a modified meta-analysis with equations selected from about 2500 available based on applicability for estimating biomass from only diameter measurements. Using regression analysis on pseudo-data generated from the selected equations, we devised the 10 new equations. This previous analysis also included two ratio equations, for hardwood and softwood species, to separate out biomass of different tree components.

The Joint Fire Sciences Program funded an extension of this work so we could update our literature synthesis to include material published since 2000 and create generalized biomass equations for regional fire-fuels managers. Using bibliographies of relevant papers and literature search engines, we added 571 new equations to the database from literature up to May 2008. The database now contains 3187 equations which are available for regional management purposes. Those which estimate total biomass in the United States and Canada include 427 equations or equation combinations for over 100 species.

Because of the difficulties inherent in using the equation database, we also began to analyze our updated equation database with meta-analysis, as in our previous work, in order to devise new equations for regional use. We based our modeling on allometric scaling theory. Genus-level models fit allometric scaling theory fairly well. Our models produced a representation of an “average biomass estimate” as a function of diameter at breast height (dbh) for each of the 21 most abundant tree genera in the United States (according to Forest Inventory and Analysis Program [FIA] data). For the rest of the genera sampled by FIA, three generalized equations for hardwood, conifer, and woodland genera were devised. Biomass estimates from our generalized conifer and hardwood equations were compared to those from generalized equations from the literature; our findings are similar to those of others, and where our estimates differed the difference was conservative. Moreover, differences seen were consistent with allometric scaling theory.

Our models represent a consistent method for estimating total biomass for tree species in the United States. However, our current results need to be studied further, particularly in comparison to the 10 biomass equations we previously developed for describing U.S. species. Also, resources only allowed us to focus on total biomass, but our database includes biomass component equations for branches, bark, foliage, and bole. Analysis of these could lead to better conversion methods that will interface with existing tree volume methods and enable conversion of bole volume to total tree biomass.

Results of our study also suggested that allometric scaling theory could provide a solid framework for a focused, consistent approach to biomass estimation. Field studies that test allometric scaling theory’s aboveground biomass estimates with measured data could ultimately lead to a standard model for estimating tree biomass using only dbh and whole-tree specific gravity as input variables.

II. Background and Purpose

Accurate estimates of biomass (and carbon) are valuable because of the importance of biomass as a key building block for measuring ecosystem processes, and also vital for forest managers in practical application. Such estimates are used in connection with both conduct of, and sales of products from, fuels treatment projects, for example. Managers are faced with the prospect of reducing fire fuels by selling biomass material not necessarily of value for traditional timber products. They want accurate consistent biomass equations for managing decisions and contract sales of biomass.

Biomass estimates are also applied in assessment of carbon stocks (carbon is approximately 50% of tree biomass) for ecological sequestration and economic purposes (e.g., carbon credits) and traditional timber product sales:

- "Cap and trade" carbon markets will require national standardized biomass estimation for consistency in the market process. Biomass/carbon is proposed for commercial sale and for public trading of carbon credits—live trees will be sold for carbon sequestration value to "off-set" carbon emissions of industrial processes.
- Management of forests for bioenergy harvests will be improved by accurate biomass estimation.

The history of tree biomass estimation should not be confused with tree volume estimation. The first biomass equations appeared in the literature in 1960s (Baskerville 1966; Whittaker and Woodwell 1968), whereas volume measurement dates back to the 18^{th} century (Laar and Akça 2007). Many associate volume estimation with biomass but biomass is technically volume times the density of the volume to be measured.

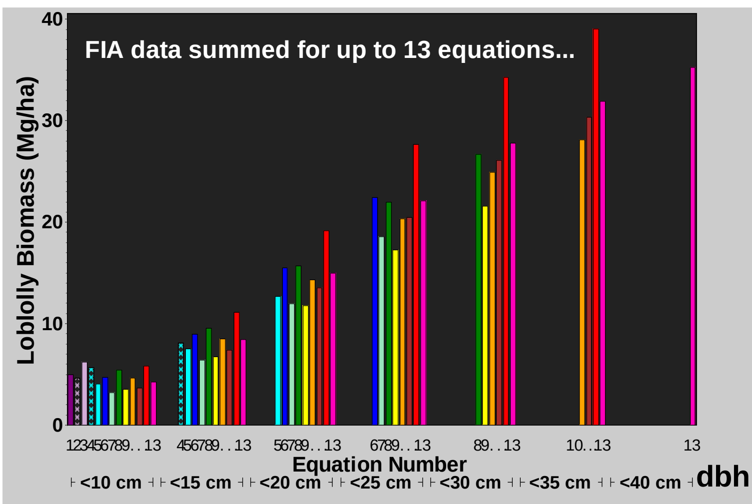
Tree volume (particularly main stem volume) is a geometric measure of length and diameter of conic sections that approximate the volume of interest. Hence, height and dbh (diameter at breast height) have been drivers of volume equations since their inception.

Biomass estimation first started with allometry, where dimensions were related to each other; for example, use of dbh to predict biomass (Whittaker and Woodwell 1968; for an overview of allometry, see Moore 2000). But volume estimation has led to the belief that the best, most robust biomass equations should include height—as is the case for volume estimation. Even though few biomass studies have included height as a predictor variable, many biomass studies include only small samples for localized areas. This has fueled speculation that—as in the case of volume estimation—height is often left out of equations for local areas, but is needed when volume equations span many sites for regional use.

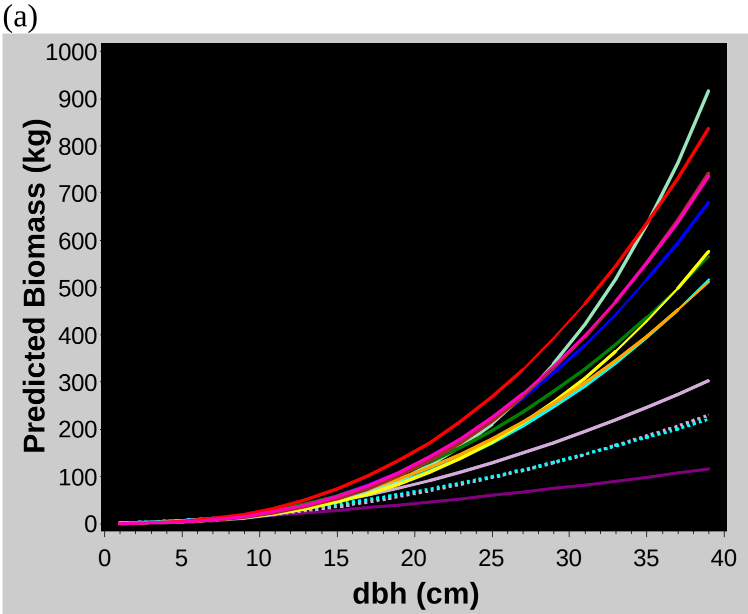
Biomass estimation began in the 1960s and 1970s with ecologists studying net primary productivity. Foresters got involved in the late 1970s and 1980s because of whole-tree utilization fueled by energy crises in the 1970s. Unfortunately, foresters' methods were not consistent with those of the ecologists. They included their traditions of excluding unmerchantable stumps and tops and of sometimes omitting foliage (particularly for hardwoods). Also, foresters, particularly those from large land management agencies, added various methods for converting volume to biomass (VanHooser and Chojnacky 1983).

The net result is a plethora of biomass equations and methods but no simple way of using this information for consistent defensible biomass estimates for all species in all parts of the United States. Instead, users generally have to pick and choose equations, and make assumptions to choose equations for gaps where no equations are available.

Thirteen loblolly pine equations from our database illustrate the problem. Comparison of these equations—for estimating average biomass per area from Forest Inventory and Analysis (FIA) data—shows differences of up to 30% or more and most of the equations apply to small dbh trees only (Figure 1a). Furthermore, biomass equations are generally fit to logarithmic models which do not extrapolate well; this can lead to gross errors if the equations are not used with caution beyond the range of data used in equation development. Comparison of the 13 loblolly equations for dbh from 1 to 40 cm (Figure 1b) shows how erroneous estimates can result from some equations when extrapolating.



(a)



(b)

Figure 1. Comparison of calculated average biomass per hectare for loblolly pine across its entire range from 13 published equations applied to Forest Inventory and Analysis (FIA) diameter distribution data. (a) Equations applied only to FIA data within the range of original equations. Note differences among equations and diminishing numbers of equations available for larger diameter trees. (b) The same equations applied from dbh of 1 to 40 cm. Note large differences among equations at larger dbh's, particularly for equations represented by purple and cyan lines that correspond to great extrapolations. Only equations represented by orange and red lines correspond to little or no extrapolation.

Therefore, just constructing a simple literature synthesis is not a substantial improvement over the existing situation. Such a database of equations can be a useful tool, but must be used with caution, and practical recommendations of which equations to use are difficult to make. Moreover, a comprehensive database is a moving target in that it requires continual updating to include each new site-specific study.

In our previous work (Jenkins et al. 2003), we compiled biomass estimation equations from the literature through 1999. In a modified meta-analysis, we generated data for diameter-based published equations at 5-cm intervals within the diameter ranges of the original equations—resulting in what we called "pseudo-data" (following the concept pioneered by John Tukey on jackknife estimation [Mosteller and Tukey 1977]). This put all literature equations on a common basis, and is somewhat analogous to having original data from which new generalized equations were developed. We then fit these pseudo-data into 10 generalized national-scale species-group-specific equations by using regression and log transformation.

The goal of this current study was improve biomass estimators for regional land management. To do this, we updated our database with equations from the recent literature, and conducted initial meta-analyses with the selected equations from the updated database. As detailed below, we utilized allometric scaling theory to guide our meta-analysis modeling, with a view to providing the foundation for development of more standardized biomass estimation.

III. Study Description and Location

A. Literature Search and Database Update Methods

Our literature search encompassed bibliographies of relevant papers and literature identified using the search engines Academic Search Premier, AGRICOLA, CAB Direct, Environmental Science Complete, Geobase, and Web of Science. We included published equations up to May 2008 developed in the United States or Canada that predicted oven-dry biomass for individual trees and components, based on diameter alone or on diameter and height.

B. Modeling Methods

Although our database includes thousands of equations that were developed for individual species in specific locations, recommendations of which equations to use where have little usefulness:

- The database does not include equations for all tree sizes for major species for all regions, and most equations do not extrapolate well (Figure 1).
- Many scientists, recognizing the lack of defensible biomass equations for a particular study need, developed and continue to develop additional equations, complicating the literature for synthesis and requiring continual updates.

- Differing modeling methodologies used in equation development add to the complexity of assessing among equations.

Instead, it made more sense to do a meta-analysis where information from all the biomass studies are used a controlled fashion to devise new equations. This is why we continued with our previous approach (Jenkins et al. 2003), first popularized by Pastor et al. (1984), where new equations were developed from predicted values of published equations.

To enhance the theoretical framework of our previous meta-analyses, we used parts of allometric scaling theory to guide our modeling. This theory explains why dimensions of biological organisms are scaled in proportion to one another (Enquist et al. 1998, 1999; West et al. 1997, 1999a, 1999b). Allometric scaling theory uses fractal dimensions of tree architecture and physics of fluid transport up a tree, in terms of a generalized biomass model, to offer an explanation of why tree biomass and volume are proportional to dbh. Parameterization of this model is postulated to hold regardless of tree species and tree size.

As in our previous work, we generated pseudo-data from equations in the literature, based on diameter only; 980 equations were used. If an equation included height, we developed a height-to-diameter equation from FIA data. Pseudo-data was generated within the range of diameters that each original equation was based on, using 5-cm intervals, or at least 5 equidistant points where original ranges were less than 25 cm. We modeled the pseudo-data using allometric scaling theory as our basis. The general model is expressed in the following equation:

$$\text{Biomass} = C\rho\,\text{dbh}^{2.67} \tag{1}$$

where

C = proportionality constant

ρ = specific gravity over the whole tree including bark, branch and foliage components

This model (eq. 1) not only makes sense from allometric scaling theory, but dbh raised to a power is also the customary way to model biomass. Furthermore, the customary power exponent is generally between 2 and 3 when estimated from data—so a historical perspective affirms 2.67 as a reasonable exponent to use.

Whole-tree specific gravity values were not available (for ρ), only rough values of wood specific gravity. Therefore, we conducted our modeling within genera (where wood specific gravity is similar) to serve as a proxy for ρ. But not all genera included enough equations for separate modeling, so we utilized a two-pronged strategy:

1. Genus-level equations were developed when enough equations were available to generate sufficient pseudo-data.
2. For the remaining species, all equations were grouped into conifer, hardwood, and woodland classes for developing generalized equations. Hardwood and conifer groups were further subdivided into specific-gravity groups.

We used FIA data to guide selection of which genera to use for developing genus-level equations. We ranked the FIA tree data by numbers of trees and 95th percentile of dbh distribution. The 21 most abundant genera included at least 4 equations each from the literature and at least one of the equations included developmental data where the dbh range spanned the 95th percentile in FIA data. Several more genera within the FIA data met our above criteria but were still excluded because they fell well below a clear break in the ranking of genera (i.e., these genera included fewer trees than those above them in the ranking that had not met criteria).

Genus-level equations included two changes from equation 1 to improve data fit. A dbh term helped with small trees and indicator variables essentially allowed for differences in whole-tree density within a genus (e.g., high density “hard maple” and lower density “soft maple”). The indicator variables were included for species within a genus that showed obvious differences from the rest (when examined graphically):

$$\begin{aligned} &\text{Biomass}_{\text{i}} = C_i \text{dbh}^{2.67} + D_i \text{dbh} + C_{ij} \text{dbh}^{2.67} + D_{ik} \text{dbh} \\ &\quad \text{where} \\ &\quad C_i, D_i = \text{parameters for } i^{\text{th}} \text{ genus} \\ &\quad C_{ij}, D_{ik} = \text{parameters for some species within } i^{\text{th}} \text{ genus,} \\ &\quad\quad \text{corresponding to definition of } j \text{ or } k \text{ indicator variables} \end{aligned} \tag{2}$$

Parameters for equation 2 were estimated from the pseudo-data using weighted regression with $1/\text{dbh}^{2.67}$ as weight. This was determined by examining residual graphs for “1/dbh” weights raised to various powers. Although addition of the dbh term and indicator variables departs from a strict allometric scaling model (eq. 1), additional variables seemed reasonable because the pseudo-data were generated from published equations (of given model forms) that would not necessarily correspond exactly to the allometric scaling model. In other words, the pseudo-data were generated from published equations that were developed through a variety of measurement and modeling techniques and may be subject to modeling biases and/or other errors. Because it was difficult to make judgments to identify outliers or inappropriate data, the additional variables were useful for addressing obvious deviations from a fit to equation 1.

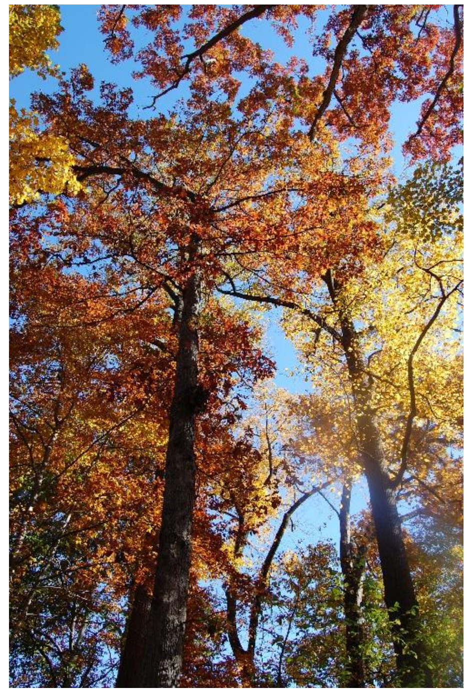
Because genus-level equations included only 21 genera, we developed equations for the remaining genera (about 70 from FIA data) by grouping all available pseudo-data (including those used to develop eq. 2) into conifer, hardwood or woodland species groups. Conifer and hardwood groups were further separated into specific gravity classes because examination of the pseudo-data showed some advantage to doing this. A polynomial regression model was fit to these pseudo-data using weighted regression. We experimented with polynomial orders and found the 4th order looked best, particularly for the woodland species, and the higher order variables showed no adverse extrapolation effects because there were ample pseudo-data to prevent radical model bends.

$$\begin{aligned} &\text{Biomass}_{\text{k}} = \beta_{0k} + \beta_{1k}\text{dbh} + \beta_{2k}\text{dbh}^2 + \beta_{3k}\text{dbh}^3 + \beta_{4k}\text{dbh}^4 \\ &\quad \text{where} \\ &\quad \text{k} = \text{conifer, hardwood and woodland groups} \\ &\quad \beta_{jk} = \text{regression parameters estimated from pseudo-data} \end{aligned} \tag{3}$$

Again, $1/\text{dbh}^{2.67}$ seemed appropriate to use as the weight term in the regression. Other weights (powers of 1/dbh) adversely affected either small or large tree predictions, and we stopped with a weight term that looked like a reasonable compromise for all tree sizes.

IV. Key Findings

A. Literature Updated



Forty-three new publications and 571 new equations were added to the database. The database now contains 3187 equations. Those which estimate total biomass in the United States and Canada include 980 equations for over 100 species in 43 genera from 128 publications. Of the 980 equations, 343 estimate total biomass directly but the rest are component equations—where usually 2 to 4 component equations add to total biomass. There were a total of 427 equations or equation combinations that estimated species-specific total biomass.

As discussed above, FIA data were used to guide which of the equations from the literature were used for estimating total biomass for the most abundant hardwood and conifer genera in the United States. The result was 388 unique equations or equation combinations that estimated total biomass for the 21 most common genera (Figure 2). In other words, the 388 equations included equations that estimate total biomass directly, plus combinations of 2–4 component equations that add together to estimate total biomass.

For those U.S. tree genera not included in the selected 21 above, all 427 equations or equation combinations were used in the modeling to develop generalized hardwood, conifer, and woodland equations. The 427 included the 388 used in modeling for the most common genera plus an additional 39 (Figure 3).

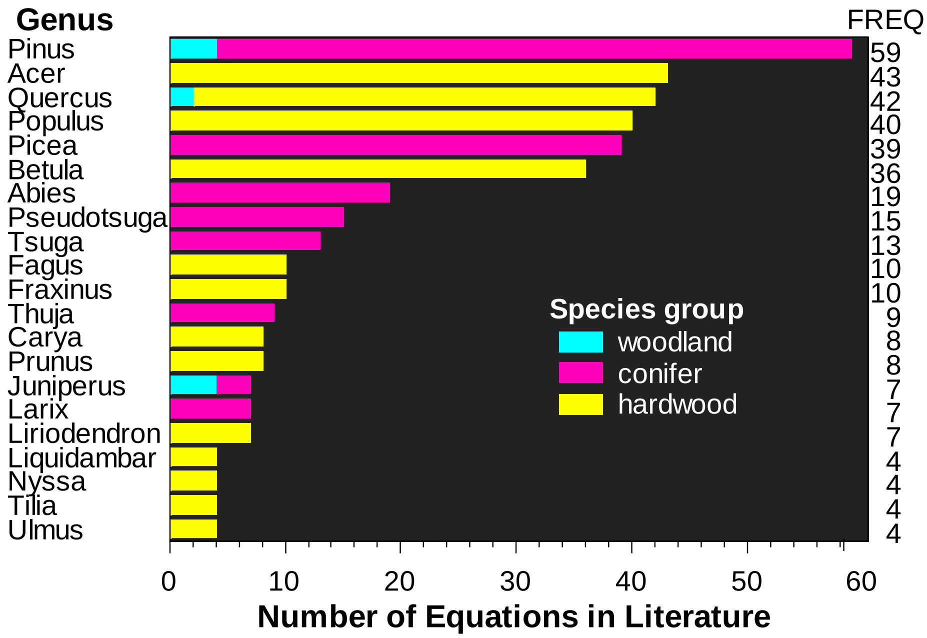


Figure 2. There were 388 equations or equation combinations in the literature used to estimate total biomass for the 21 most abundant U.S. tree genera. Included are equations that estimate total biomass directly, as well as combinations of component equations that sum to total biomass. Woodland species included pinyon, western oak species, and western juniper species, but not eastern red cedar.

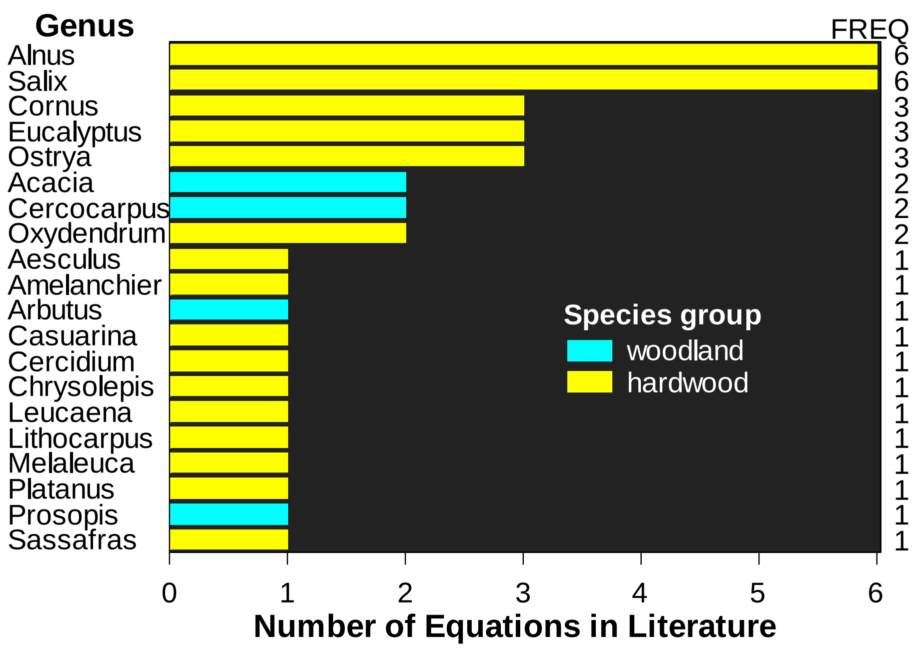


Figure 3. Biomass equations in the literature used only for developing generalized hardwood, conifer, and woodland equations. These 39 equations were for those genera not among the 21 most abundant. Included are equations that estimate total biomass directly, as well as combinations of component equations that sum to total biomass.

B. Genus-level Equations Developed

Unique equations were developed for 8 conifer and 13 hardwood genera (total=21), among the most abundant in the United States. Indicator-variable modifications resulted in additional equation curves within some genera, for a total of 15 equation curves each in the conifer and hardwood groupings (Figures 4 and 5). These equations were fit from pseudo-data using $1/dbh^{2.67}$ as regression weight. Regression parameters are given in Table 1.

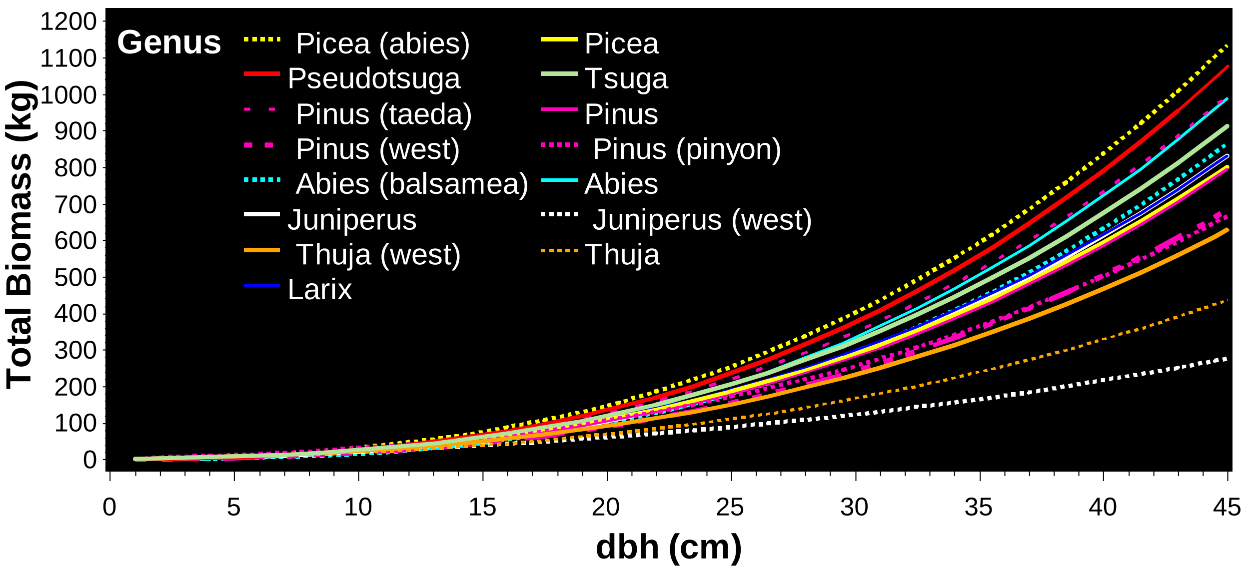


Figure 4. Model results for the conifer group.

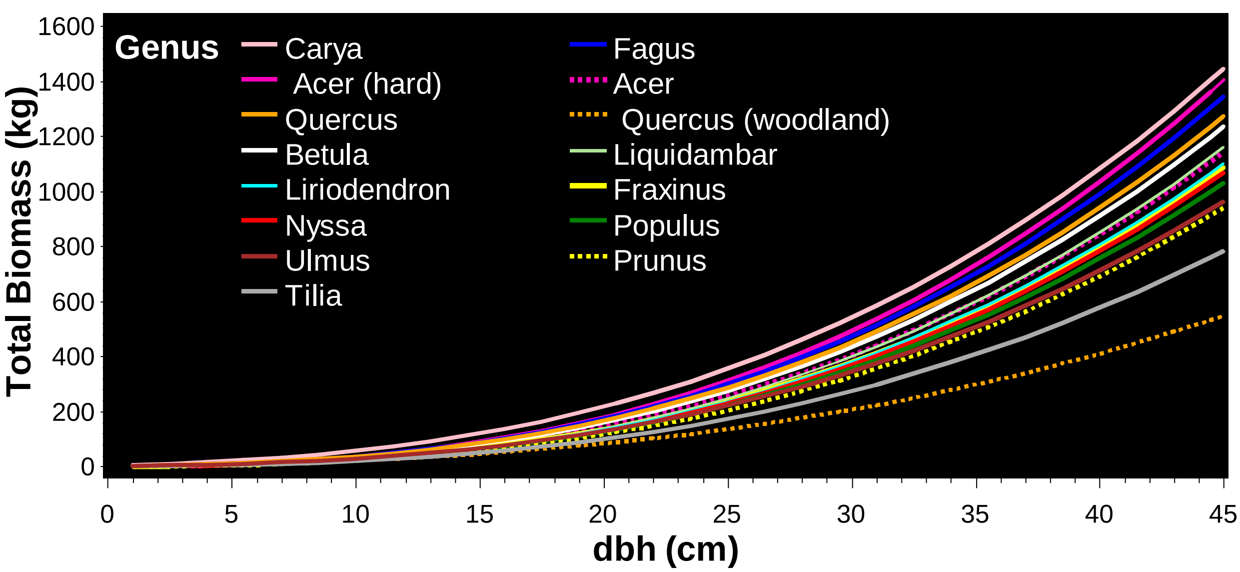


Figure 5. Model results for the hardwood group.

Table 1. Biomass model parameters for major U.S. tree genera, for estimating biomass in kg per tree from dbh measured in cm. The sample size "n" is number of pseudo-data points generated for 388 "equations or equation combinations" compiled from the literature that estimate total biomass (equations that estimate total biomass directly, plus combinations of 2–4 component equations that add together to estimate total biomass).

	Parameters			
Genus	C_i	D_i	**n**	R^2
Abies	0.0385	0.1532	198	0.98
Acer	0.0437	0.6772	353	0.98
Betula	0.0471	0.7056	290	0.97
Carya	0.0539	1.4530	69	0.94
Fagus	0.0509	0.9175	95	0.98
Fraxinus	0.0419	0.4427	72	0.98
Juniperus	0.0302	0.9796	60	0.82
Larix	0.0316	0.7542	54	0.95
Liquidambar	0.0449	0.1989	33	1.00
Liriodendron	0.0424	0.3204	58	0.98
Nyssa	0.0415	0.2010	23	0.99
Picea	0.0299	0.8764	277	0.97
Pinus	0.0300	0.6135	413	0.97
Populus	0.0396	0.3832	270	0.96
Prunus	0.0363	0.3631	56	0.96
Pseudotsuga	0.0405	0.9986	123	1.00
Quercus	0.0480	1.0302	334	0.95
Thuja	0.0152	1.0703	81	0.94
Tilia	0.0300	0.3670	24	0.99
Tsuga	0.0341	0.7997	126	0.99
Ulmus	0.0366	0.7423	30	0.98

$$\text{Biomass}_{\text{i}} = C_i \text{dbh}^{2.67} + D_i \text{dbh} + C_{ij} \text{dbh}^{2.67} + D_{ik} \text{dbh}$$

where

C_i, D_i = parameters for 21 genera above

C_{ij}, D_{ik} = parameters for j or k indicator variables defined below

$C_{i1} = -0.0054$ for eastern *Abies* species; 0 otherwise

$C_{i2} = 0.0099$ for *Acer* specific gravity > 0.5; 0 otherwise

$C_{i3} = -0.0278$ for *Juniperus* species EXCEPT *J. virginiana*; 0 otherwise

$C_{i4} = 0.0132$ for *Picea abies*; 0 otherwise

$C_{i5} = -0.0044$ for western *Pinus* species EXCEPT pinyon; 0 otherwise

$C_{i6} = 0.0082$ for Pinus *taeda*; 0 otherwise

$C_{i7} = -0.0113$ for pinyon pine species; 0 otherwise

$C_{i8} = -0.0272$ for western *Quercus* species; 0 otherwise

$C_{i9} = 0.0074$ for western *Thuja* species; 0 otherwise

$D_{i1} = 4.7911$ for *Juniperus* species EXCEPT *J. virginiana*; 0 otherwise

$D_{i2} = 1.3286$ for pinyon pine species; 0 otherwise

C. Generalized Equations Developed

For the remaining native and exotic tree genera in the United States, a second model was developed by combining pseudo-data from all 427 selected equations or equation combinations. Species were grouped into conifer, hardwood, and woodland categories generally according to FIA definition and further divided by specific gravity of wood.

Equations or equation combinations included those for conifer species with specific gravity of <0.3 (90 equations or equation combinations), conifer species with specific gravity ≥ 0.3 (74), hardwood species with specific gravity of <0.3 (62), hardwood species with specific gravity between 0.4 and 0.5 (75), hardwood species with specific gravity of ≥ 0.5 (111), and woodland species (15) (Table 2, Figure 6).

Table 2. Biomass model parameters for model with all species grouped into hardwood, conifer, and woodland, for estimating biomass in kg per tree from dbh measured in cm. The sample size "n" is the number of pseudo-data points generated for 427 "equations or equation combinations" compiled from the literature that estimate total biomass (equations that estimate total biomass directly, plus combinations of 2–4 component equations that add together to estimate total biomass).

	Equation parameters						
Group	β_{0k}	β_{1k}	β_{2k}	β_{3k}	β_{4k}	**n**	R^2
conifer with specific gravity < 0.4	0.6073	-0.5168	0.2995	-0.00102	0.0000701	753	0.96
conifer with specific gravity ≥ 0.4	0.5956	-0.6420	0.2854	0.00292	0.0000184	549	0.97
hardwood with specific gravity < 0.4	0.3152	-0.2999	0.1922	0.00780	-0.0000248	403	0.96
hardwood with specific gravity 0.4 - 0.49	0.1132	-0.2020	0.1964	0.01074	-0.0000648	552	0.97
hardwood with specific gravity ≥ 0.5	0.2015	-0.2236	0.2203	0.01529	-0.0001199	933	0.96
woodland for all specific gravities	2.8309	-1.9473	0.4559	-0.00940	0.0000757	94	0.70

$$\text{Biomass}_k = \beta_{0k} + \beta_{1k}\,\text{dbh} + \beta_{2k}\,\text{dbh}^2 + \beta_{3k}\,\text{dbh}^3 + \beta_{4k}\,\text{dbh}^4$$

where

k = conifer, hardwood or woodland species grouped by wood specific gravity

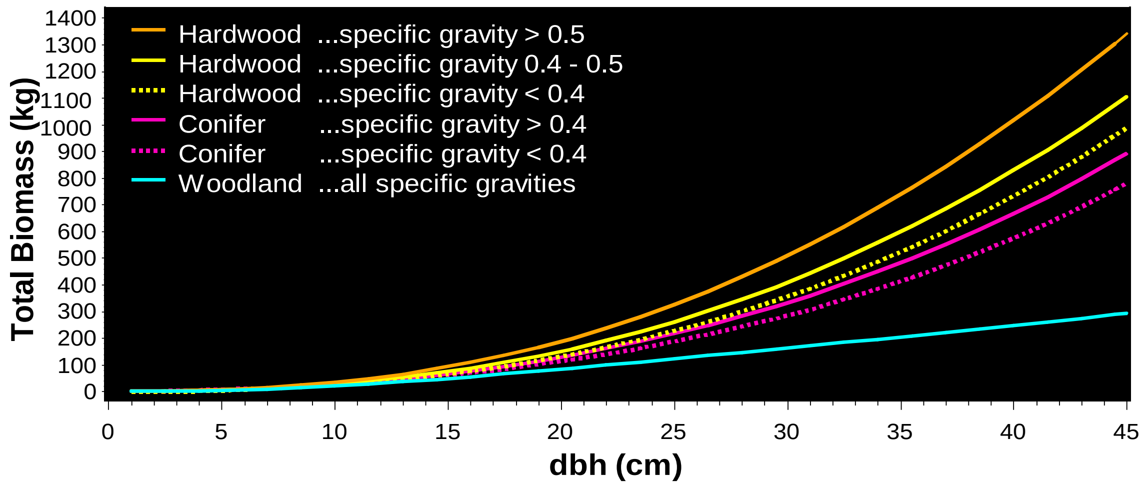


Figure 6. Model results for all species grouped into hardwood, conifer, and woodland.

D. Other findings

Need for height in final equations

We found few papers that included biomass equations based only on height and dbh in the newer literature, and as a result decided that it was not the best use of our limited resources to reexamine older literature for those excluded previously.

Using FIA data for generating pseudo-data

This was done for loblolly pine only (Figure 1). Although useful for comparison among equations, it was too computationally demanding and not compelling enough to warrant further testing as a basis for generation of pseudo-data for alternative meta-analysis. Therefore we elected to concentrate our resources on our previous protocol for generating pseudo-data.

Green weight conversions

Because biomass estimates are typically given in dry weight units for consistency, we examined the literature for recommendations on appropriate conversions for practical application. Initial investigation into conversions of dry weight to green weight showed this to be more a practical preference than a research question. A user can select any green weight moisture content—known to vary widely from summer to winter (Patterson and Doruska 2005), as well as by location, weather, and intraspecies variability (Smith 1985)—and adjust our dry weight results accordingly. For rough estimates, we suggest using “50% of green weight equals dry weight” which is a commonly used conversion that is supported in the literature (e.g., Smith 1985) and by anecdotal data in some of the biomass equation papers included in our database. For example, 40% to 60% ranges were reported in a New York study that we reviewed that included most major eastern U.S. species (Monteith 1979) and for a large southern U.S. hardwood biomass study dry weight was about 50% of green weight (Clark et al. 1986).

V. Management Implications

A. General Discussion

The literature synthesis, updated to May 2008, provided 571 new biomass estimation equations that will be available for regional management purposes. This addition increased the number of available equations by about 20%. Those which estimate total species-specific biomass in the United States and Canada include 427 unique equations or equation combinations for over 100 species. Our EXCEL database of equations is available upon request, and we can offer brief instruction for the equation selection process. Total biomass can be estimated from these but equations must be selected and combined carefully, with multiple options per species. Also, considerable substitution must be made for species with no published biomass equations—which, as shown from our comparison to FIA data, include over 60 tree genera.

In contrast, our meta-analysis allowed us to devise comprehensive and consistent methodology for estimating total biomass for all species in the United States and Canada. Our models estimate biomass directly for the 21 most abundant genera in the United States; these represent an "average biomass estimate" for each genus available in the literature. We provide generalized conifer, hardwood, and woodland equations for the rest.

Although the genus-level models fit allometric scaling theory fairly well, our analyses of pseudo-data are still a work in progress. Our intention was to publish our modeling results and equation database at the conclusion of this grant, and that could have been done, although our additional FIA funding for continuation of this work complicates publication now. FIA has funded work for refinement of our equation database so that it can be used to revise ratio equations (Jenkins et al. 2003) for estimating foliage, bark, and branch biomass components. Although our database includes component equations, component definitions can differ widely, requiring more coding of what should and should not be used for meta-analysis for estimating biomass components. This "re-coding" (which is in progress) is also correcting some data-entry errors which likely will change parameter results in Tables 1 and 2. At the conclusion of the FIA study all equations will be published, and this product will be more comprehensive than that which would have resulted prior to the additional work.

Interestingly, the greatest use of this database is probably not for literature synthesis nor even meta-analysis but as background for testing new ideas for biomass estimation. As our database attests, the science of biomass estimation has progressed little since inception—only more species-specific equations have been developed with little thought given to more generalized approaches. This is understandable, given that "new species/site-specific" biomass equations can be developed faster from conventional methods than from theoretical research, and neither resources nor motivation are often available for more generalized approaches. However, in the long term biomass estimation based on sound theory may be able to provide a more efficient, cost-effective tool for land managers. Our database of the biomass literature will provide information against which to compare any newly devised theoretically based biomass equations. Not only will the "pseudo-data" from our database be useful for comparison, but existing equations might provide helpful clues in guiding testing and application of a theoretical model applicable to many species.

The allometric scaling theory used to guide our modeling is one of the first theoretical ideas to aim at generalized biomass equations for all species. This theory is based on distinguishing individual species differences with a whole-tree specific gravity value (equation 1). Although obtaining whole-tree specific gravity may be difficult, allometric scaling theory indicates tree size is not a parameter in the model, which could be a huge boon for rapid application if only small trees need be sampled for whole-tree specific gravity. In Section VII (Future Work) below, we have summarized a brief proposal for a preliminary field test of allometric scaling theory.

B. Biomass Roundtable #2 Recommendations

At the JFSP Biomass Roundtable #2 meeting in Boise, Idaho, in November 2009, participants felt that although a generalized model is useful in promoting standardization, more site-specific biomass estimation tools are needed. Because of immediate needs to predict available biomass, it was suggested that the model could be refined for the most important genera by using locally available data, but it is unlikely that such data would be available or usable for this purpose.

Specific biomass estimation needs identified in the draft summary report from the meeting included the following:

1. Develop a basic methodology to calibrate models based on regional and/or site-specific conditions.
2. Review and recommend the most robust species-specific models/equations.
3. Refine models to better estimate how much biomass will be accessible for other uses (e.g., how much will make it to the roadside), not just the total available in a project area.

We suggest best meeting all of these needs, and addressing them at a broader scale, by launching into the study of allometric scaling theory. The alternative approach would, for all three items, require millions of dollars for collection of new biomass data. Regional site-specific biomass data collection would be required for item #1. Our 21 genus-specific biomass equations are the most robust equations that can be generated with currently available literature; development of species-specific equations (item #2) would require new data collection. With our additional FIA funding, we are currently refining our models to estimate biomass ratio components, which addresses item #3. However, these models will be crude and further refinement will again require new biomass data collection.

VI. Relationship to Other Recent Findings and Ongoing Work on this Topic

Our previous study (Jenkins et al. 2003) has up until now been the most comprehensive work in this area, and the research presented here has enabled us to update that work. However, we did compare some of the generalized biomass estimation equations (found in literature for select conifer and hardwood species) not included in our modeling effort to those we developed.

Our database included several generalized conifer and hardwood equations for mostly eastern species. In some cases, authors reported many species-specific biomass equations and then combined all data into generalized equations for conifer and hardwood. In a few instances, authors located raw biomass data and reanalyzed for conifer and hardwood groups. We compared these published equations to the generalized conifer/hardwood equations we generated through our meta-analysis, and included select genera for our equations to give perspective. Because the published generalized equations were mostly for eastern species, we selected *Pinus taeda* and *Thuja* equations (Figure 4) to illustrate a range of eastern conifer equations. Likewise, *Carya* and *Tilia* equations (Figure 5) were selected to represent a range of eastern hardwoods. We compared equations for a dbh range of 0 to 30 cm to emphasize differences within the dbh range of most eastern U.S. species—as FIA data showed 90% of trees in the United States are less than about 30–35 cm dbh.

The conifer comparison showed our generalized equations generally estimating less biomass than the published equations do, but it is difficult to make a judgment about which equations are better. The generalized equations in the literature do not necessarily include a wide range of species as ours do. Often an author presented equations for individual species and then combined data for a generalized equation. We could say more about this comparison if we were to reassess these generalized equations for species ranges, specific gravity ranges, etc., but this was beyond the scope of our project. However, this comparison does show our generalized conifer equations to be reasonable and if in error, conservatively so, as low predictions are more desirable than wild over-predictions. Our *Thuja* curve does stand out as perhaps a bit low, but there is no way to check the accuracy of our equation without new biomass data collection for *Thuja* species.

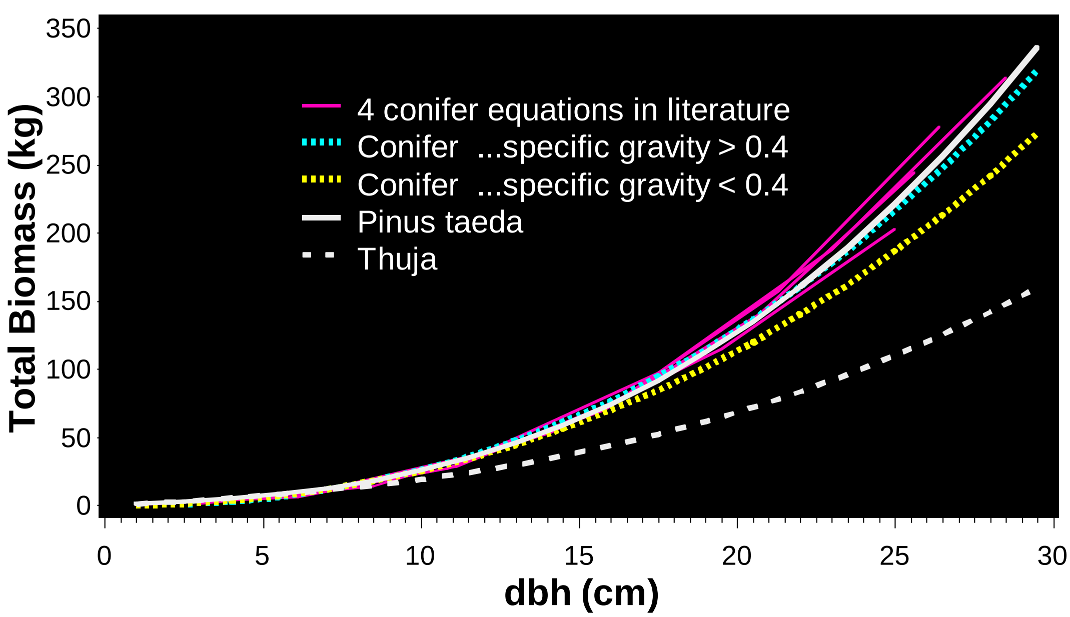


Figure 7.Total biomass estimates from generalized conifer equations in the literature compared to those from equations developed in this study's meta-analysis. The latter equations include those for generalized use (Conifer) and for the extremes of genus-level equations (*Pinus taeda* and *Thuja*).

Allometric scaling theory may provide an explanation for the low biomass estimation displayed in the *Thuja* curve. According to allometric scaling theory, we would expect low predictions for *Thuja* (for a given dbh) because it was the least dense conifer species at 0.29 specific gravity. Also, *Pinus taeda* with 0.47 specific gravity was one of the more dense species which would put it at top of the mix according to allometric scaling theory—and indeed that is where it falls in Figure 7. Recall from equation 1 that specific gravity is the only value that varies among species in the dbh-to-biomass allometric relationship, assuming the constant “C” does not vary much.

The hardwood comparison results also support allometric scaling theory. More generalized hardwood equations were available than were found for eastern conifers. Again, our generalized equation estimates were within the range of the estimates from published equations or a little lower (Figure 8). *Carya* represents one of the highest wood density species with 0.62 specific gravity, while *Tilia* is one of the lower with 0.32 specific gravity. Our estimate for the low-density *Tilia* is among the lowest of the curves, while our estimate for the high-density *Carya* is the highest in the comparison, as predicted by allometric scaling theory. (There was one very low-predicting hardwood equation which was even lower than our *Tilia* equation. A quick check showed no error in our database for the low hardwood equation but there could be an error in the published equation.)

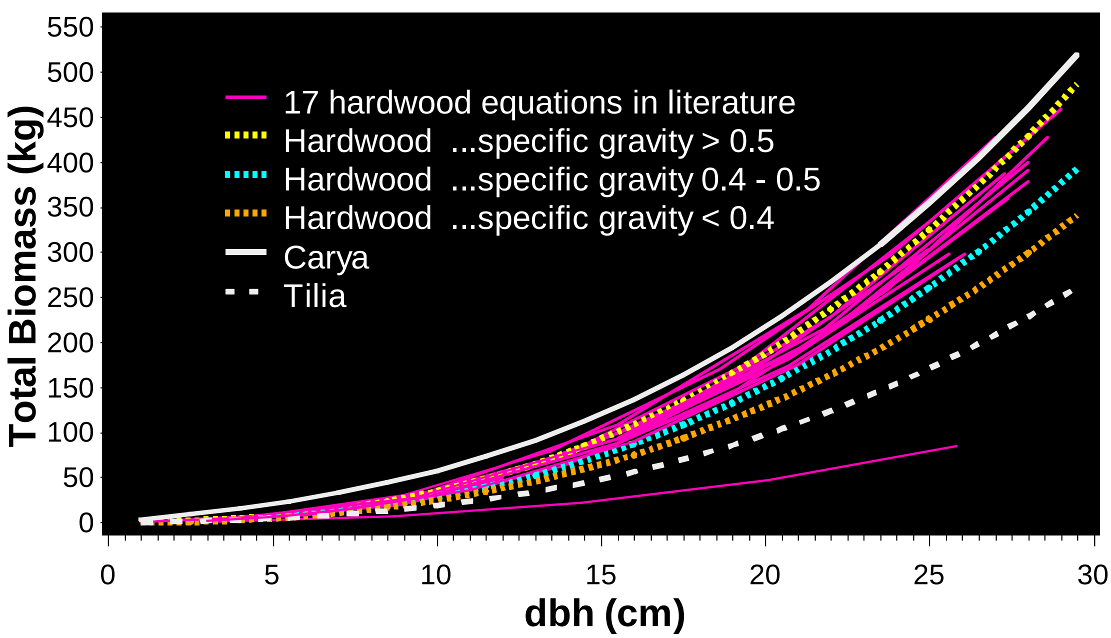


Figure 8. Total biomass estimates from generalized hardwood equations in the literature compared to those from equations developed in this study’s meta-analysis. The latter equations include those for generalized use (Hardwood) and for the extremes of genus-level equations (*Carya* and *Tilia*).

In summary, our findings support other work devising generalized biomass equations. But more significantly, we may have some of the first credible evidence that allometric scaling theory is a good basis for future study of tree biomass. Allometric scaling theory holds promise for making more sense out of the massive numbers of biomass equations in the interim, and for consistent defensible biomass estimation in the long term.

VII. Future Work Needed

A. Current Results

Our current results could be studied further, particularly in comparison to the 10 biomass equations we previously developed for describing U.S. species. Although our preliminary models look reasonable and promising, some of the genera model estimates are very close and could probably be combined.

Also, our method of generating meta-data could be overly influencing some of our results. In particular, equations that apply only to small trees may be weighted more heavily than others. The minimum of 5 data points per equation results in more 1-cm interval (or less) pseudo-data from equations that apply only to small trees than 5-cm interval data from equations for trees spanning more than 20 cm dbh.

More equitable methods for generating pseudo-data could be explored, perhaps using FIA data. For example, Figure 1a summarizes pseudo-data for 13 equations for loblolly pine; these could also be used to develop a generalized loblolly pine equation. Unfortunately, it will be no simple task to apply our database to FIA data due to the wide diversity of equation types, diameter ranges, and so forth—but it can be done. The loblolly equations were physically tailor-coded into a program for calculating biomass from FIA diameter data, but a more efficient electronic merger must be devised for the remaining equations.

Because we are in the process of revisiting papers with our additional funding, there will also be an opportunity to examine the possibility of using more equations for generation of total biomass pseudo-data by combining some data "among papers." For example, many studies omitted foliage biomass for particular species, but another nearby study or studies that estimated foliage for the species in question might be reasonably used. This might also be done with bark and branches. The net result could greatly increase numbers of equations used to generate pseudo-data—currently only 980 out of 3,187.

B. Biomass Component Estimation

A much-needed application of our database is development of improved methodology for estimating biomass components—particularly for conversion of bole wood volume estimates to total tree biomass. Component biomass estimation may also help managers determine how much biomass in an area is usable or salable; e.g., subtraction of biomass of branches and foliage that are left in the woods from total biomass of trees. In our previous work (Jenkins et al. 2003), we devised hardwood and conifer ratio equations for this purpose. However, we used only a portion of available equations for biomass components because our database structure did not allow us to mix and match our selections of biomass component equations, which are reported in a wide variety of ways. For example, sometimes bark is included with stem biomass, sometimes it is separated, or sometimes it is omitted. Likewise, foliage and branches are reported as live or dead, combined with other components, or separated into size or age classes. We did devise methodology to structure our database so that consistent definitions of foliage, branches, bark, and stem wood could be extracted, but further work on this aspect (which is being pursued with our additional funding) will involve physically examining perhaps up to 100 papers.

C. Field Test of Allometric Scaling Theory

Although further database development will facilitate short-term applications, this approach is a very conservative traditional approach with limited payoff—we really need accurate field measurements guided by a sound theory to achieve long-term consistency in biomass estimation. Our study strongly suggests that allometric scaling theory can provide the framework for a clear, focused approach to biomass estimation. Ideally, if funding could be obtained, we would like to conduct a preliminary study where the allometric-scaling-theory model would be tested for the first time for aboveground biomass estimation with measured data. Results, if promising, would lead to a design for a definitive study and eventual development of a standard model that might more accurately estimate tree biomass using only dbh and whole-tree specific gravity as input variables. (A previous proposal to JFSP outlined both the preliminary and definitive work. However, results from the more modest preliminary research effort would provide good insight into whether biomass estimation through allometric scaling theory is worth pursuing, and/or what the next steps towards a standard model should be.)

For example, we would like test the allometric-scaling-theory model with concurrent measurement of biomass and of whole-tree specific gravity; the latter has never been measured. For a preliminary test, we would like to study several species that represent a range from high to low specific gravities and include a variety of branching and growth rate patterns. For $50,000 we could destructively sample and measure about 10 to 15 trees. Results would provide a snapshot comparison as to whether the allometric-scaling-theory model holds for several species and a basis for devising sampling strategy for additional data collection.

Even if the model does not hold perfectly, we expect that whole-tree specific gravity will be a powerful predictor of tree biomass, because it is a biophysical measure of tree structure linked to tree architecture—which should greatly improve biomass estimation. Also, the detailed data collected (biomass and corresponding specific gravities throughout entire trees) would support generation and testing of new methods for estimating biomass components (bark, branches, and foliage) from total biomass estimates.

Study of allometric scaling theory would certainly enhance our understanding of forest biomass dynamics and greatly advance carbon assessment related to fire fuels, global carbon sequestration, and general ecosystem health. Such understanding will be vital for land managers dealing with changing climatic conditions.

VIII. Deliverables Cross-Walk

	Deliverables Stated in Proposal	Accomplishment Status
1	Update earlier database and synthesis of individual-tree biomass equations for North America for a scientific/manager audience, and assemble into an easily searchable, spreadsheet-style database.	**Completed literature search.** Database now includes 3187 equations. **Assembly for publication in progress.** FIA funding will enable completion and inclusion of foliage, bark, and branch component biomass estimates so that the database will be more comprehensive.
2	Develop generalized equations for species groups by using statistical graphic and clustering techniques.	**Completed.** Equation modeling under this study was completed; however, final equation parameter estimates (affected by inclusion of new data) will be published at conclusion of the FIA study extension.
3	Use the FIA database to establish initial species groups for maximum numbers of biomass equations.	**Completed.** FIA data were successfully used to select genera for guiding development of genus-level biomass equations.
4	Combine results from #2 and #3 above for final determination of number of equations that can be devised for species groups on a region-by-region basis for application by land managers.	**Completed.** Genus-level equations generated appear useful, but too few equations were available to do further meta-analysis at regional scales.
5	Examine the need for height in final equations produced from the meta-analysis.	**Completed.** Few newer papers included biomass equations based only on height/dbh, so it was not the best use of resources to reexamine older literature.
6	Estimate two sets of parameters for final equations from meta-analysis regression: (1) from generated data (within dbh and height range of original developmental data) and (2) from FIA data.	**Completed for loblolly pine.** Although interesting, this was too computationally demanding to repeat for more species with our limited funding.
7	Estimate variances for equation-predicted values by a bootstrap resampling method and use to calculate confidence intervals.	**Evaluated.** We developed a jackknife resampling method for variance estimation in our previous work (Jenkins et al. 2003) that was not published because of peer-review concern. Therefore, we wanted to revisit variance estimation with bootstrap resampling method, but when much more of our resources went to business administration than planned, this task was not a priority for our remaining resources.
8	Devise green weight conversions for practical application.	**Completed preliminary investigation.** Initial investigation showed this to be more a practical preference than a research question. As a rule of thumb, we

		suggest assuming dry weight is 50% of green weight.
9	Repeat steps 1 through 8 (where possible) for estimating shrub biomass.	**Completed preliminary assessment.** We found very little interest in shrub biomass from key contacts supplied by JFSP, so our limited resources were not applied to this task.
10	Examine results for further study of biomass estimation by using allometric scaling theory.	**Completed. Allometric scaling theory was used** in devising genus-level equations. We would like to continue study of this promising idea with additional funding.
11	Document biomass equations for credibility (best available science) in a journal publication.	**In progress. Preliminary study results were presented** at the Carbon in Northern Forests Conference, 10–11 June 2009, Traverse City, MI; at the 4th International Fire Ecology & Management Conference, 30 Nov–4 Dec 2009, Savannah, GA; and at the JFSP Biomass Roundtable #2, 2–3 Nov 2009, Boise, ID. When the FIA study extension generates final, more comprehensive equations, results will be submitted to a professional journal for peer review and publication.
12	Upon manager recommendation, prepare a printed document aimed at manager audience.	**Completed.** Results from this report were presented at the JFSP Biomass Roundtable #2, 2–3 Nov 2009, Boise, ID; and a printed meeting summary has been drafted.
13	Upon manager recommendation, prepare a multi-media DVD and/or web site with equations and guidance for their use.	**Pending.** Our meta-analysis was not necessarily endorsed at the JFSP "Biomass Roundtable #2" meeting, so further dissemination beyond planned publication of generalized equations is not needed. Only knowledge of algebra is required to use the equations, and users will find our publication. (Our previous 2003 Forest Science article was consistently one of the most requested papers from Society of American Foresters last year.)

IX. Budget Summary

Following is a budget summary for completion of the literature synthesis and preliminary modeling. The U.S. Forest Service is funding the continuation of this project. Therefore, remaining funds will be added to that project for writer/editor contracting and travel related to JFSP meetings.

Budget Item		Expenditure
Salary/Benefits:	Chojnacky (717 hrs)	59,245
	Holland (600 hrs)	30,774
	Jenkins (UVM PI, no hrs available)	10,037
Computers/Supplies/Training/Misc		5,568
Domestic Travel		6,324
Contract Services		4,028
Total Expenditures		$115,976
Grant Total		$120,000
Unspent funds project termination 12/31/2009		$4,024

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